A Heavy Axion from the Twin Higgs

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With Brian Batell, Thomas Cochran, and Logan Page

Scales of Beyond the SM

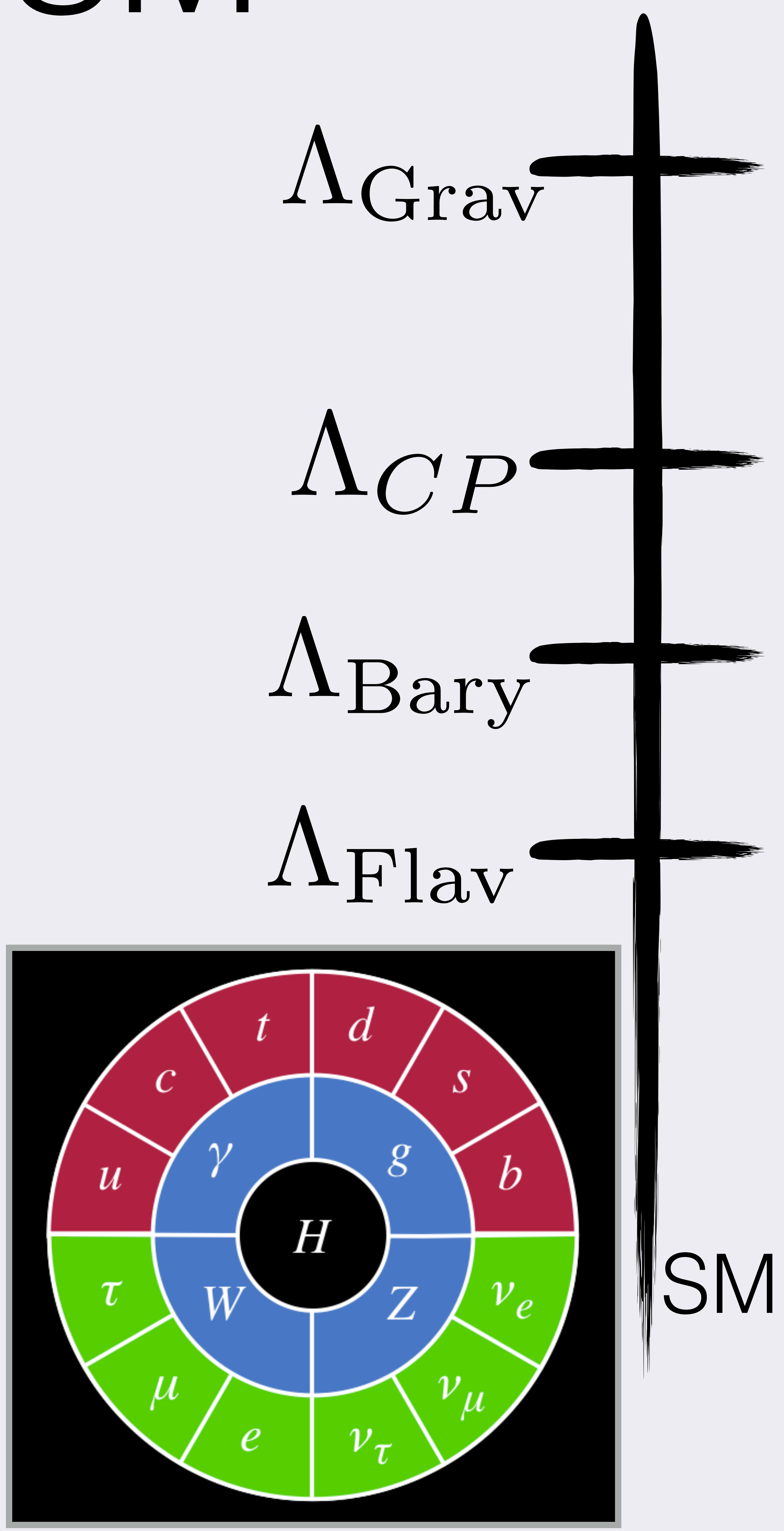
The Standard Model is a triumph,
but must be extended

Some extensions relate to things we know are missing

- Dark Matter
- Neutrino Masses
- Baryogenesis

Other have to do with puzzling measured quantities

- Higgs mass (EW hierarchy)
- QCD theta term (Strong CP problem)
- Flavor Structure



Axion Quality

Already introduced…

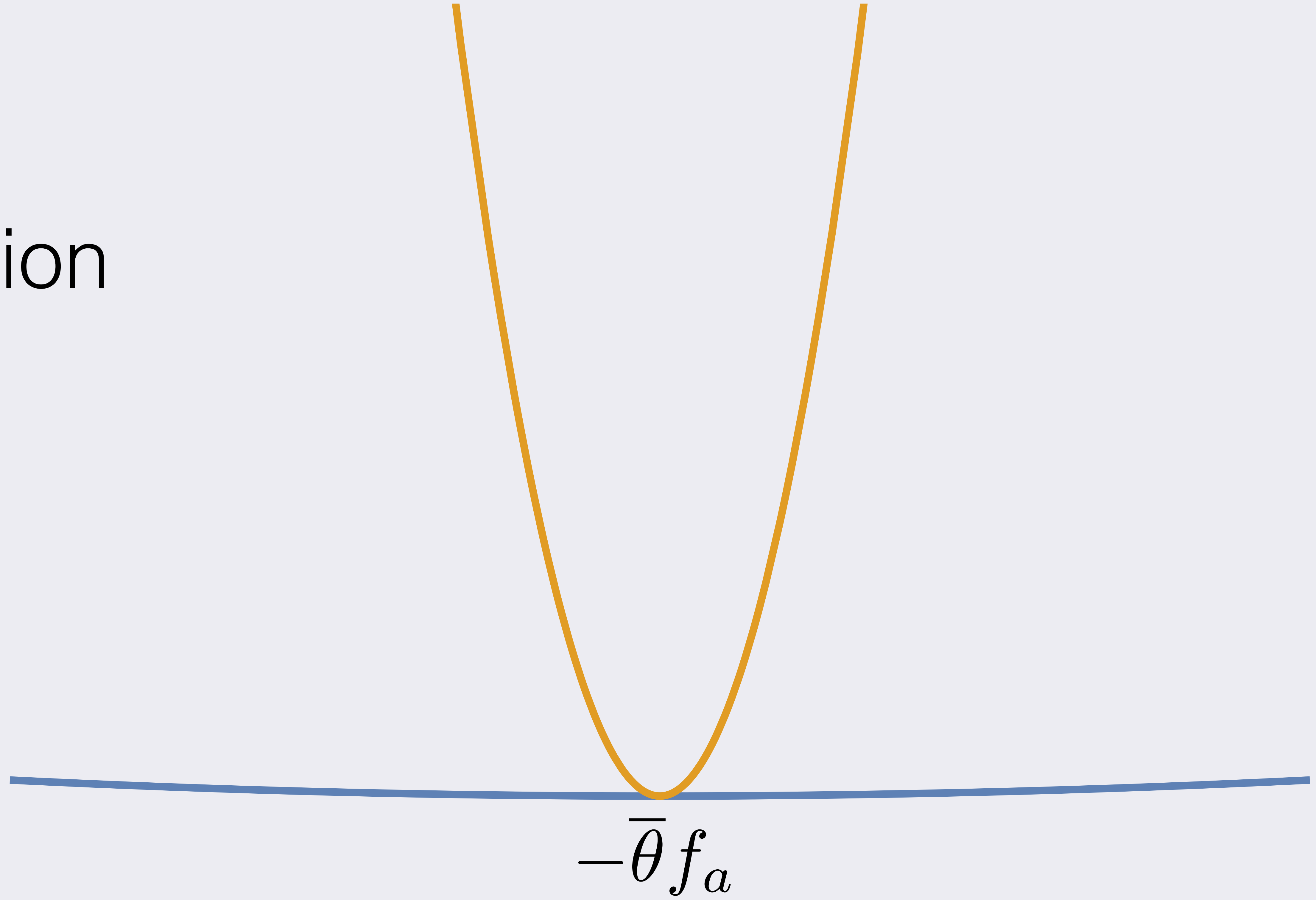
$$\frac{\alpha_3}{8\pi}\left(\frac{a}{f_a}+\overline{\theta}\right)G_{\mu\nu}\widetilde{G}^{\mu\nu}$$

The axion potential is supposed to make $\langle a\rangle = -\overline{\theta} f_a$

If potential is nearly flat, then small corrections (even Planck suppressed operators) can prevent relaxation to true minimum

Increasing the axion mass makes relaxation much more robust

Original QCD axion can have a very flat potential, this the quality problem



Heavy Axion

Several ways to make axions heavy

Make high scale instanton effects larger than in standard QCD

Assume the axion couples to another gauge group in addition to QCD

$$\frac{\alpha_3}{8\pi}\left(\frac{a}{f_a}+\overline{\theta}\right)G_{\mu\nu}\widetilde{G}^{\mu\nu}+\frac{\alpha'}{8\pi}\left(\frac{a}{f_a}+\overline{\theta}'\right)G'_{\mu\nu}\widetilde{G}'^{\mu\nu}$$

The second group can provide larger contributions to the axion mass

But to solve the CP problem we need $|\overline{\theta}-\overline{\theta}'|<10^{-10}$

References in TASI lectures Hook 1812.02669

Heavy Axion from Mirror

Assume a Z_2 symmetry in the UV then $\bar{\theta} = \bar{\theta}'$

Seven loop running of theta makes very small changes if symmetry is softly broken

$$\left(\frac{a}{f_a} + \bar{\theta}\right)\left(\frac{\alpha_3}{8\pi} G_{\mu\nu}\widetilde{G}^{\mu\nu} + \frac{\alpha_3'}{8\pi} G'_{\mu\nu}\widetilde{G}'^{\mu\nu}\right) \qquad \beta = -\left(11\frac{N_c}{3} - \frac{2}{3}n_f\right)\frac{\alpha^2}{2\pi}$$

If mirror Higgs VEV is large then twin quark masses are higher and the twin strong coupling confines at a higher scale

This produces a heavier axion, **avoids** axion quality problem

Kind of **emphasizes** the electroweak hierarchy problem

Why are the two Higgs VEVs so different?

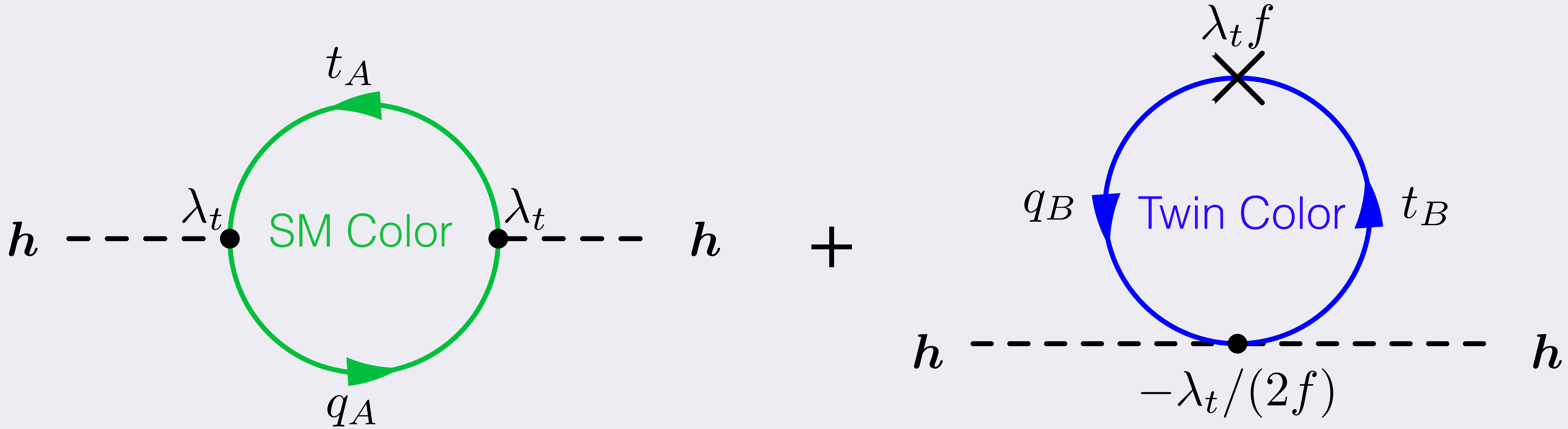
Twin Higgs

Chacko, Goh, Harnik,
hep-ph/0506256

Symmetry based solutions to ‘little’ Hierarchy puzzle

Assume Higgs and Twin have nearly global SU(4) symmetric potential

Quark symmetry partners are the twin states



Only a modest hierarchy between the Higgs and its twin

Recent Review: Batell, Low, Neil, CV 2203.05531

Twin Higgs Axion

Mirror Twin Higgs simply matches onto usual mirror axion story

$$\left(\frac{a}{f_a}+\overline{\theta}\right)\left(\frac{\alpha_3}{8\pi}G_{\mu\nu}\widetilde{G}^{\mu\nu}+\frac{\alpha_3'}{8\pi}G'_{\mu\nu}\widetilde{G}'^{\mu\nu}\right)$$

Axion mass is

$$m_a^2 \simeq 10^{-4}\text{GeV}\times\left(\frac{5\ \text{TeV}}{f_a}\right)^2\left(\frac{\Lambda'/\Lambda}{20}\right)^3\left(\frac{v'/v}{3}\right)$$

The twin confinement scale is roughly

$$\Lambda' = \Lambda\left(1+\ln\frac{v'}{v}\right)$$

A mild hierarchy of Higgs VEVs leads to a mild increase in axion mass

Extended Twin Color

More interesting axion masses if we extend color in both sectors to SU(4)

In visible sector only, SU(4) is spontaneously broken to SU(3)

Also a spontaneous breaking of the Z_2 symmetry

Very similar to methods in:
Batell, CV 1904.10468 & Batell, Hu, CV 2004.10761

SU(4) running is faster than SU(3), leads to higher confinement scale

Much higher mass for
the same ratio of Higgs VEVs

$$\beta = -\left(11\frac{N_c}{3} - \frac{2}{3}n_f\right)\frac{\alpha^2}{2\pi}$$

$$m_a^2 \simeq 10^{-4}\text{GeV} \times \left(\frac{5\ \text{TeV}}{f_a}\right)^2 \left(\frac{\Lambda'/\Lambda}{20}\right)^3 \left(\frac{v'/v}{3}\right)$$

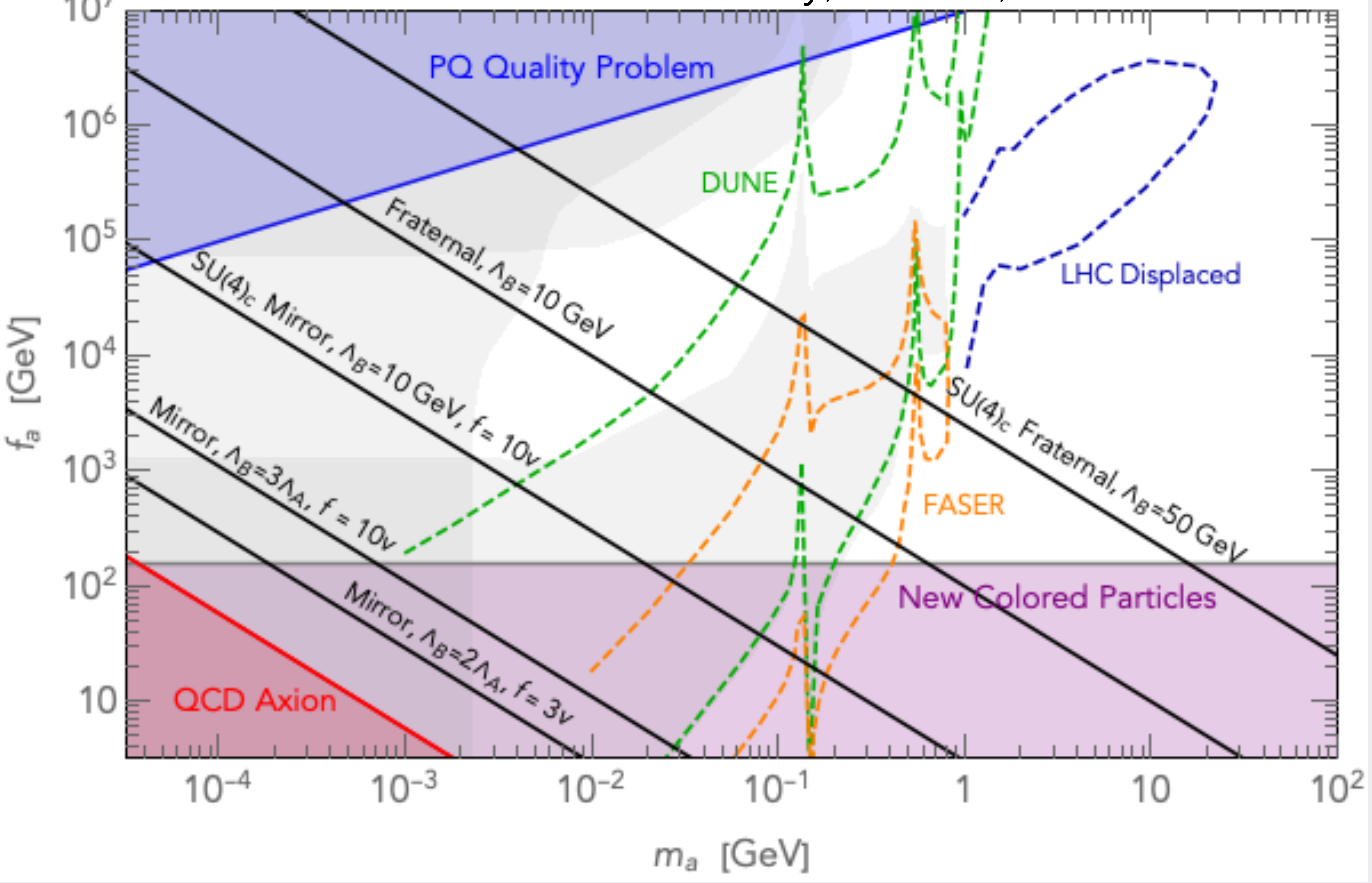
Results

Grey regions excluded by experimental searches

Purple region predicts new colored particles below 2 TeV

Dashed lines correspond to planned searches

From Kelly, Kumar, Liu 2011.05995



New Visible Fermions

$$\langle \phi \rangle = \begin{pmatrix} 0 \\ 0 \\ 0 \\ w \end{pmatrix}$$

The fourth components of the quark fields are lifted by

$$\lambda_{\widehat{Q}} \overline{\mathcal{Q}} \phi \widehat{Q} + \lambda_{\widehat{U}} \overline{\mathcal{U}} \phi \widehat{U} + \lambda_{\widehat{D}} \overline{\mathcal{D}} \phi \widehat{D} + \text{H.c.}$$

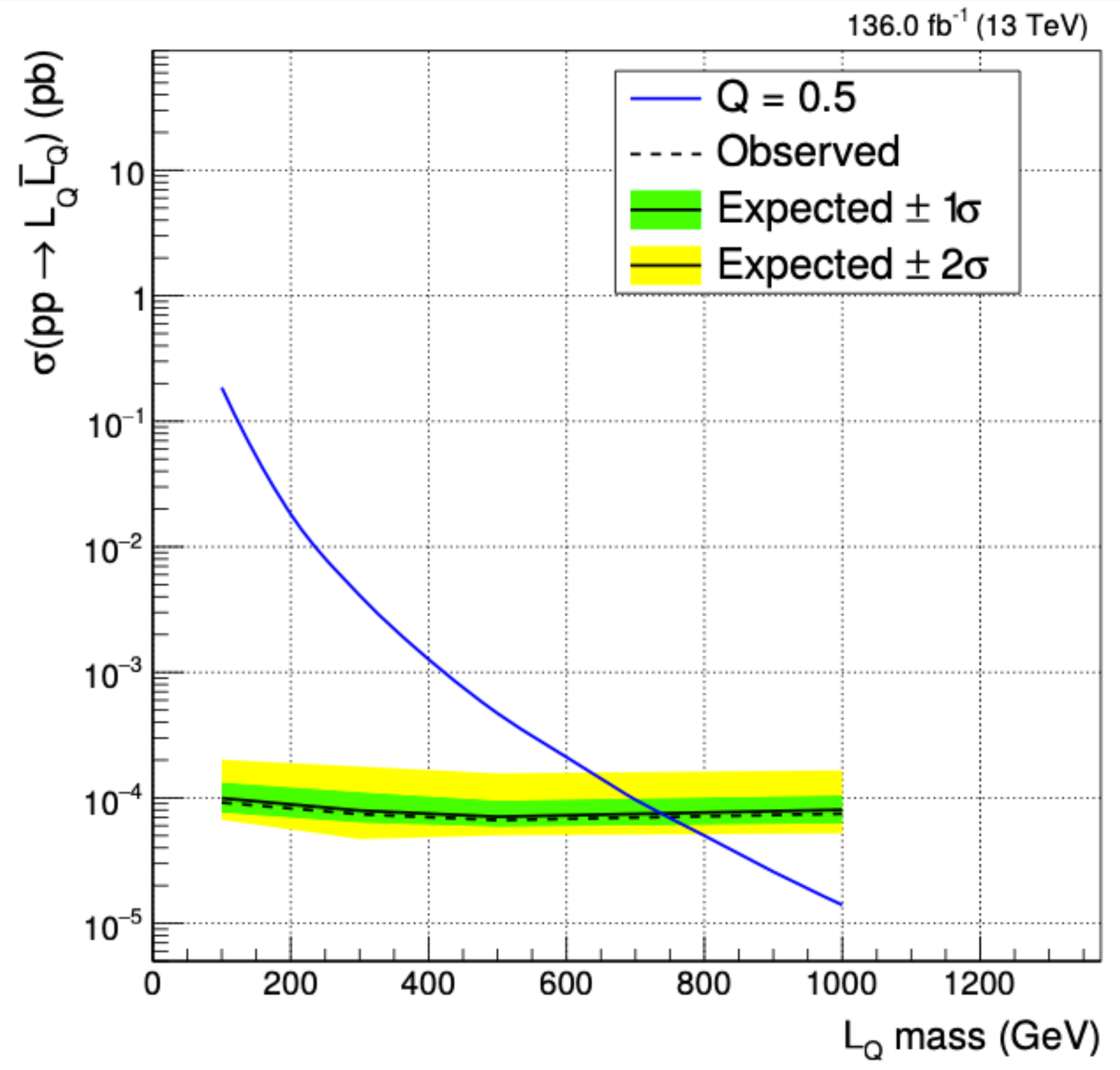
$$\mathcal{Q} = \begin{pmatrix} Q_{\text{SM}} \\ Q_4 \end{pmatrix}$$

where ϕ is the SU(4) fundamental that gets a VEV

BSM fermionic states get masses controlled by Yukawa couplings and the color breaking VEV

They have electric charge of ½

Bounds on such states are currently 1 TeV might easily be discovered up to 1.5 TeV



D. Vannerom, Search for new physics in the dark sector with the CMS detector: From invisible to low charge particles, Ph.D. thesis

New Visible Vectors

Breaking SU(4) to SU(3) in the visible sector also produces interesting states that can be discovered at the LHC or future experiments

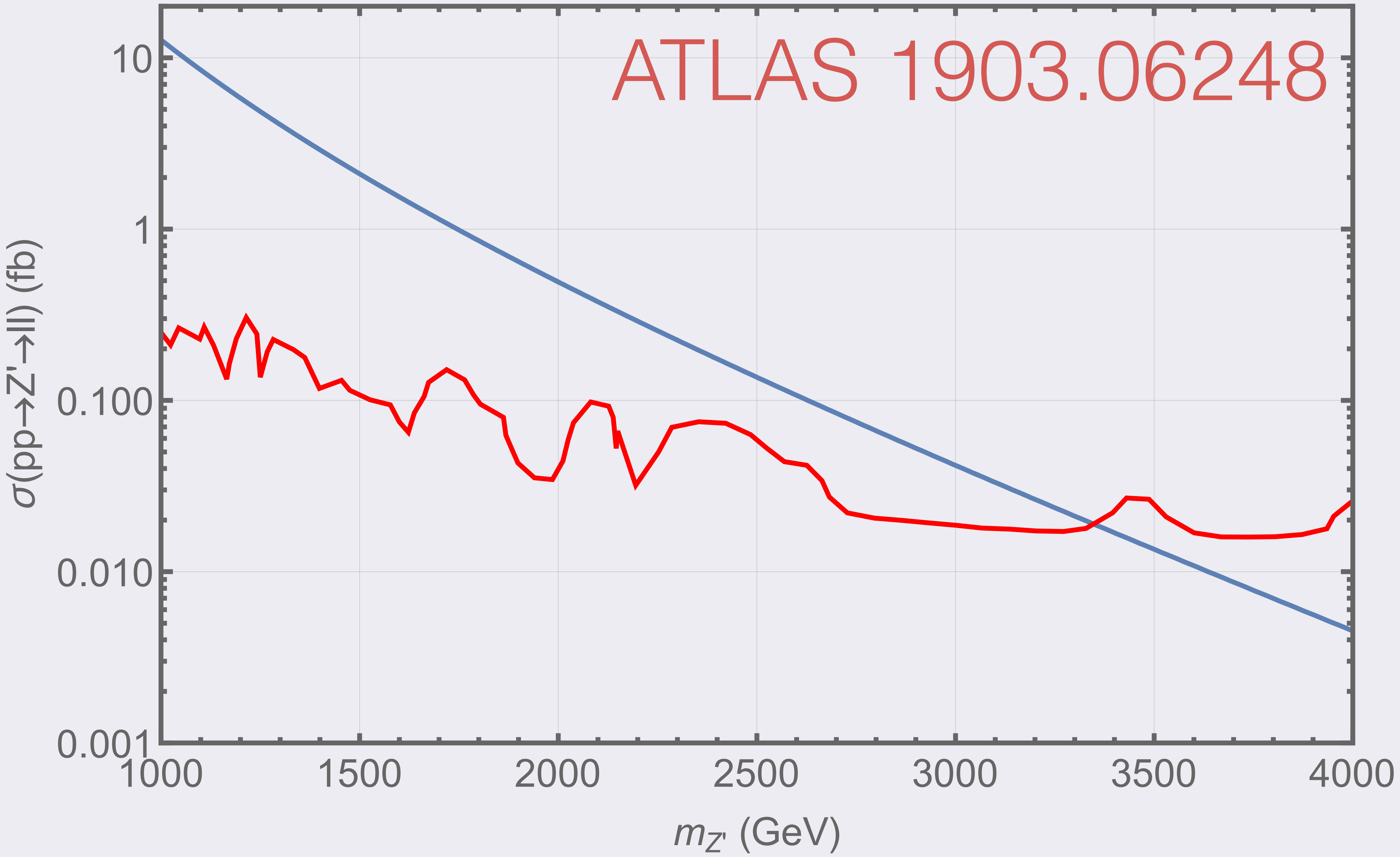
Seven of the SU(4) gluons become massive

Six make up a complex vector ξ. Color fundamental with electric charge ⅙

The seventh becomes a electrically neutral Z’

Dominantly decays to quarks, only 10^{-3} branching to leptons

Dilepton and dijet bounds imply ~3 TeV mass for Z’ and ξ



Summary

The absence of CP violation in QCD is puzzling

The hierarchy between the EW scale and other scales is puzzling

Heavy axions can explain the absence of CP violation in QCD without concerns about small deviations from its potential

Twin Higgs models with extended color can increase the axion mass while offering some explanation of the EW scale

Also predicts interesting collider signals at the LHC and beyond